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Abstract

Structural health monitoring (SHM) is a competitive approach for damage detection in aircraft structures, wherein online information is collected and compared with an existing database for the undamaged structure, to obtain real-time information about the presence of damage. The goal of this research is to develop numerical models of inverse problems under uncertainty for damage detection in aircraft structures, which could later be part of an on-board system for SHM. In this work, the numerical modeling has two main branches: I. The direct problem: a numerical model (using Finite Element Method - FEM, or Boundary Element Method - BEM) is required to obtain information on the distribution of the quantity of interest throughout a given damaged structure. The numerical model of the direct problem is expected to reproduce the reality of an aircraft structure. II. The inverse problem: a model is required to locate the structural damage given the information on the quantity of interest at particular locations (sensor locations). To increase the reliability of the detection approach, a combination of independent optimization and identification procedures can be used. III ó The modeling of uncertainties: the treatment of the stochasticity in the problem variables and parameters may include procedures such as response surface methodology (RSM) and Monte Carlo simulation (MCS), and is embedded in the inverse problem techniques, such as multi-objective stochastic optimization, artificial neural networks (ANN) and Kalman filter (KF). Related to this project, some inverse methods with application to potential problems were developed and discussed in this word. Although originally developed for a different context, the inverse methods developed could be extended to structural problems. Also related to this project, an initial study was performed for the direct problem of analysis of vibration data related to dynamic components of a helicopter, on the context of HUMS ó Health and Usage Monitoring Systems. Although the monitoring of dynamic components in HUMS is more concentrated on forced vibration analysis, several aspects of the discussion of this type of direct problem could be extended later for structural vibration analysis.

1. Introduction / research outline

1.1 Background

Aircraft structures are subject to damage during their useful life. The timely detection of damages in aircraft structures is an important feature for flight safety. The usual inspection procedures during regular maintenance intervals may lead to problems such as:

- Inspection intervals might be too large, thus allowing damage to propagate unnoticed for an unacceptable time interval or through an unacceptable extension;
- Critical structural components might be difficult to access, thus imposing disassembly / assembly procedures which are time-consuming and expensive, sometimes requiring jigs and other special tools for proper assembly of the structure;
- Some non-destructive techniques (such as eddy current, for example) may be portable, not requiring full disassembly of the structure, but might be inaccurate or might depend strongly on the technician's experience for a damage to be detected properly;

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- Other non-destructive techniques (such as X-Ray, or magnetic particles, for example) might require full component disassembly and removal to an industrial facility to perform the structural inspection.
- Some structural components, for example those made of composite materials, may present internal damage which is difficult to detect using standard inspection techniques, as ultrasonic tests.

1.2 Scientific Challenge

Structural health monitoring (SHM) is a competitive approach for damage detection, wherein online information is collected, compared with an existing database for the undamaged structure, and from this comparison, real-time information about the presence of damage is obtained, its location, length, speed of propagation, and, ultimately, the remaining operational life of the structural component.

Some challenges related to an efficient on-board structural health monitoring system include:

- The system must be small in size and weight, must consume a small amount of power, and must not interfere with the aircraft electrical system;
- The system must be reliable, and the information on the located damage must also be reliable: thus, the system must have redundancies in the built-in numerical codes, which must be based on separate independent numerical models.

1.3 Research Objective

To study and develop numerical models of inverse problems for damage detection under uncertainty in aircraft structures, which could later be part of an on-board system for structural health monitoring.

The research includes modeling of the direct and inverse problems, and the related uncertainties. This on-going research is an extension of a previous research work, now including modeling under uncertainties. The general objective is to model structural health monitoring (SHM) techniques for a representative real structure being simulated, with uncertainties in the material properties, loading and damage parameters. The goal for the direct model is to reproduce the behavior of an aircraft structure; the goal for the inverse model is to obtain reliable damage information, using a combination of independent optimization and identification procedures to infer damage location and size; and the goal for the modeling of uncertainties is to compare algorithm robustness and sensitivity to randomness in problem variables and parameters, for the identification and probabilistic methods. Related to this project, technical reports, research papers and student thesis/dissertations were developed, involving inverse methods with application to different types of problems, such as potential problems, and also involving the analysis of different direct problems, such as the analysis of vibration data related to dynamic components of a helicopter, on the context of HUMS ó Health and Usage Monitoring Systems.

1.4 Air Force Relevance

The research is concentrated in numerical models for inverse problems under uncertainty. The timely detection of damage is an important feature for flight safety. The codes developed for damage detection in aeronautical structures could be part of an on-board system for SHM. This

research is also relevant in aircraft maintenance, with the possibility for using such on-board SHM system as a substitute for some costly structural inspections during regular, scheduled maintenance. An initial analysis of collected data was also performed, on the context of forced vibration of dynamic components.

1.5 Approach

The approach in this research work is to investigate the feasibility of numerical procedures for damage detection in aircraft structures. The numerical modeling consists of three main parts:

- I. **The direct problem:** a model for the structure is required to obtain information on the distribution of the quantity of interest (for example, the acoustic pressure or the stress field) throughout the structure, given the boundary conditions and the presence of the damage. The Finite Element Method (FEM) and the Boundary Element Method (BEM) can be used as alternatives for modeling the structure. Some possibilities for these models are the elastic modeling of cracked plates, and the acoustic modeling of damaged plates (may include acoustic propagation from a generated signal or from aerodynamic noise). The advantages of the Boundary Element Method over other numerical methods (such as finite elements) are well known from the literature, especially for the treatment of high gradient problems, such as the stress gradient due to cracks. The numerical models for potential, acoustics, or elasticity can be used in combination or independently, to simulate the multiple physics present in lamb waves, stress waves, acoustic emission, etc, involved in the usual structural health monitoring (SHM) techniques ([1] ó [3]).
- II. **The inverse problem:** a model is required for the procedure of locating the damage in the structure given some (partial) information on the quantity of interest (for example, the stress field) at some particular locations (for example, sensor locations). For this inverse problem, both optimization and identification techniques can be used. The optimization procedure minimizes a functional, obtained from differences between measured values and values generated by the numerical code at different assumed damage locations. The minimum value of the functional will occur when the distance between the real damage and the assumed damage location in the numerical code is also a minimum, thus giving an indication of the damage location and size. Some possibilities to model this optimization problem include heuristics such as evolutionary algorithms (genetic algorithms, or differential evolution, for example). Additionally to the optimization procedures, identification techniques, such as artificial neural networks (ANN) and Kalman filter (KF) procedures, can also be used for the inverse problem, by setting the desired location and size of the damage as parameters to be identified.
- III. **The modeling of uncertainties:** both the direct and the inverse problems are in fact stochastic, and involve some level of treatment of the randomness of the parameters and variables of the models. Certain variables in the problem (such as aerodynamic loads) and some parameters of the structure (such as elastic properties and constitutive behavior) do not present determinist values and must be treated as random variables, or must be identified. For the treatment of the stochastic nature of the problem, parameter identification procedures (such as Kalman filter) and stochastic optimization procedures (such as Response Surface methodology, or Monte Carlo simulation) may be used. For a given objective function to be optimized (written as a response surface, for example), its randomness (for example, given by its variance) can also be expressed as another objective

function (written as a separate response surface, for example). Thus, a stochastic optimization problem can be recast as a multi-objective optimization problem. Procedures to obtain the response surfaces might include design of experiments combined with regression, or the learning of the structural behavior through a neural network procedure.

1.6 Resources / Research team

This report refers to a three-year period (2010-2013) of an on-going research. The research work is being developed at the Computational Mechanics group at UNIFEI. The research is concentrated in the use of optimization and identification techniques for the inverse problem, and in the modeling of uncertainties. Research team includes Professors Ariosto Bretanha Jorge (PI), Sebastião Simões da Cunha Jr., Patrícia da Silva Lopes and André Garcia Chiarello, and also a couple of graduate students. Some of the previous research (2006 to 2009) in this area has been performed also with the support from AFOSR, mostly concentrated in deterministic Boundary Element Methods, for the direct problems, and in Genetic Algorithms, for the inverse problem. During the three years of the project, the research also lead to advising of graduate students in related areas, concentrated in the use of deterministic and stochastic optimization and identification techniques for a given direct modeling (elasticity and acoustics, for example), the modeling of uncertainties and a combination of FEM and BEM as direct models.

Some collaborative research work was also established, related to this project:

- i. with Prof. D. Greg Walker, at Vanderbilt University, including the co-advising of a graduate student in inverse methods for parameter identification techniques for mechanical systems. This collaborative work was concentrated in comparing different techniques (Kalman filter, particle filter, etc) and different measurement models for a transient heat transfer problem with a concentrated heat source (which could be considered, in terms of the study of the inverse method techniques, as similar to a problem with concentrated load). Several conference papers were presented, and several journal articles were published, as a result of this collaborative research work.
- ii. With Prof. Marcelo Kobayashi, at University of Hawaii, on the use of topological optimization techniques associated to the damage detection problem. The research is in its initial phase, and the goal of the research in this topic is to recast the problem of finding the optimum number and location of sensors (to maximize the probability of detection or another variable of interest) as a topological optimization procedure, where the topology will be the number of sensors, the dimensioning of the elements will be the location / distance between sensors, and the sizing will be the sensor properties (for example, for a acoustics transducer, its power output, frequency, type of signal ó transient, steady state, pulse, etc). A PhD student is currently being advised at UNIFEI in this topic.
- iii. With Prof. Donizeti de Andrade, from Instituto Tecnológico de Aeronáutica - ITA, São José dos Campos, Brazil, on detection of failures of a helicopter main rotor, leading to a co-advising of a graduate student at ITA.
- iv. With Professors Bento de Mattos and Airton Nabarrete, also from ITA, together with Prof. André Chiarello from UNIFEI, on the discussion and analysis of vibration data related to dynamic components of a helicopter, on the context of HUMS ó Health and Usage Monitoring Systems. This part of the work was performed with support from HELIBRAS/EUROCOPTER, which gave access to helicopter vibration data as recorded in their HUMS system.

1.7 Cost / Funding

For this project, funding was U\$ 40,000.00 per year, during three years. The funds were directed to stipends and general expenses related to the project (eg., travel expenses, computer consumables, books, etc) for the researchers involved.

1.8 Contact Information for the P.I.

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2. Research description

Modeling the damage detection problem: general aspects

The detection of damage in structures has applications in flight safety and aircraft maintenance. The development of damage detection techniques can help to increase the structural reliability (safety), contributing to a better structural integrity analysis and evaluation of the remaining service life of a structure. The analysis of a damaged structure must involve the numerical treatment of data gathered from sensors spread throughout critical points in the structure, and the comparison of this data with numerical results used as reference (eg., results from the undamaged structure, or with known damage). These damage detection techniques may involve real-time monitoring of the integrity of critical airframe elements which are difficult to access.

2.1 Damage detection: overview of the Direct and Inverse Problems

To analyze a damage detection problem in a structure, first the modeling of the direct problem is required, to obtain the behavior of this structure in the presence of one or more pre-established damages, with assumed format, size, and position (see references [4], [5] for damage detection problems).

The modeling of the problem can be based on a combination of Finite Element and Boundary Element Methods as a FEM/BEM direct model (the BEM model being best suited for large gradients in the field being considered, while the FEM accommodating well properties/material changes throughout the structure).

In this work, two methods of analysis were given particular attention, for the direct method:
1) the study of stress/strain distributions in damaged structural elements, performed with a numerical model (FEM/BEM) for elastostatics or fracture mechanics (see references [6], [7] for numerical methods, fracture mechanics); and

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2) the study of the distribution of some scalar field in the damaged structure, performed with a numerical model (FEM/BEM). For problems governed by the Laplace or Poisson equations, a potential field, such as the temperature distribution, is the quantity of interest. For acoustics, the scalar potential field of interest may be the sound pressure in the structure due to sound waves (emitted from a pre-established source). The presence of the defect in the structure influences the distribution of these scalar fields. (see references [8], [9] for a FEM/BEM method applied to acoustics)

Regardless of the nature of the physics involved, from the point of view of the inverse problem, the direct model is only a *black box* to obtain numerical information of the quantities of interest, at selected locations.

For the study of the inverse problem, the model consists of two parts:

- a) Monitoring the structural integrity, from experimental measurements, with a certain number of sensors spread throughout the structure. With this, some knowledge is obtained about the distribution of stresses or strains (for example, by means of strain-gages) or about the distribution of a variable derived from the acoustic pressure throughout the structure (for example, by means of microphones, accelerometers, or other sensors).
- b) Computation of a functional obtained from adding differences (evaluated in all measurement points) between the values evaluated using the numerical model from the direct problem, for a given damage that was assumed, and the experimental values measured in the same points for the structure with the real damage or crack. This functional is a function of the crack or damage location, either numerical or measured from the real structure. This functional is expected to increase in value when the assumed numerical defect is far away from the real defect. Also, this functional is expected to reach its minimum value when both defects (for example, the numerical and real cracks) coincide. Thus, the inverse problem is, in fact, an optimization problem for the search of a global minimum for this functional. In this work, local optimization methods (such as linear or quadratic sequential programming) may be used to compare with global optimization heuristics (such as genetic algorithms and differential evolution).

The study of the randomness of the variables involved in these problems is of great importance, in order to the computational modeling being used to be representative of the real structure. To account for these uncertainties, parameter identification techniques (such the Kalman filter approach) could be used, together with the treatment of the randomness of these variables (using stochastic optimization techniques, such as Response Surface methodology, or using Monte Carlo simulation).

2.2 Damage detection by means of optimization techniques

In an experimental analysis, the data gathered come from sensors spread throughout the structure, located at a number of points. The experimental analysis is not being undertaken at this moment, thus the size and location of the real damage in the plate are being assumed and simulated using the numerical model (FEM/BEM). In order to solve the inverse problem, an optimization algorithm (GA, for example) is used. The evaluation/fitness function is formulated as a functional of the differences between measured (simulated) and calculated information at

interior points. Figure 1 represents damaged thin plates with points where the measurements are being performed. A population of numerical damages is formed by individuals constituting possible solutions for the problem. These individuals are chromosomes, and each gene in a chromosome represents one variable in the problem (such as position and size of a hole). Figure 1(a) to 1(c) represents three possible configurations of chromosomes, wherein the location and size of the hole varies, but the sensors (where information on the quantity of interest is collected) remain the same.

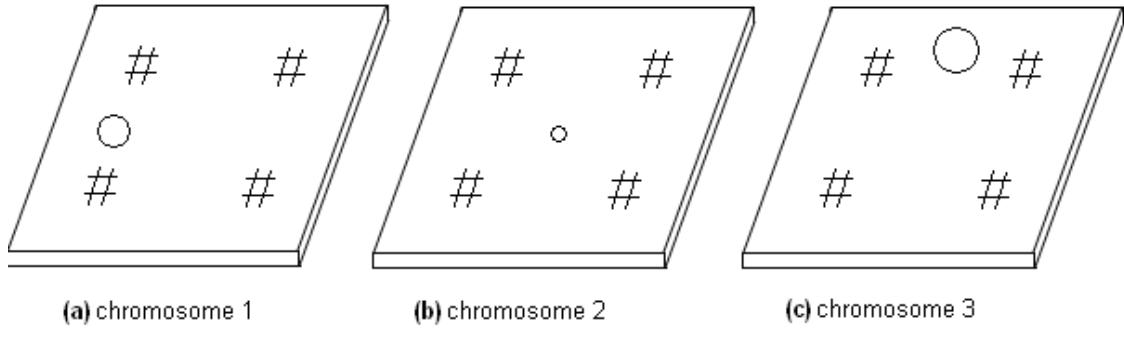


Figure 1 - Plate with a hole: three possible configurations for the chromosomes

Some representative preliminary results are shown in Fig. 2, wherein a BEM code for acoustics was used on a plate model with a central hole (the *real* hole). A sound source was placed as shown in Fig. 2a. Several *numerical* holes were placed in different locations as shown in Fig. 2b, and the results for the functional values are shown in Fig. 2c. In this case, a plot of the potential quantity with time was available at designated locations (*sensor* locations), both for the *real* and *numerical* holes, and the areas between the curves are representative of the functional. One can note the correct correlation between the functional and the damage location, as the functional decreases when the *numerical* hole gets closer to the *real* hole, as expected.

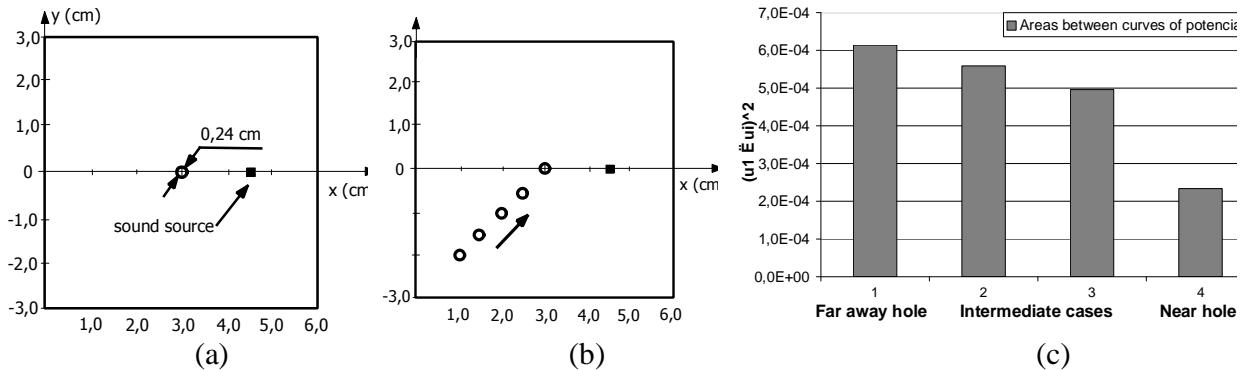


Figure 2 - Plate with a hole: (a) setup; (b) numerical holes approaching the real hole; (c) functional decreases near real hole.

Some of the plate properties may not be known a priori. Material properties and geometric parameters are suited to be obtained in the real structure by means of parameter identification procedures. Other variables (loading, boundary conditions) may need to be treated as random

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variables in the damage detection code. Also, the number, size and location of the different damages may need to be treated either by parameter identification or as random variables.

2.3 Modeling of Uncertainties

In the modeling of an engineering problem, the various parameters and variables of the system being studied are not deterministic. A proper treatment of this variability leads to robust optimization techniques, where the goal is to obtain not only optimum values for the objective functions, but also minimum variations in these objective functions in the neighborhood of these optimum points. In this context, the words *stochastic optimization* and *robust optimization* lead to the same idea, as the goal of the treatment of the stochasticity of the variables and parameters of the problem is to obtain robust optima. In this case, the optima are points in the feasible region, wherein the values of the objective functions are insensitive to variations around these points. The model has to look not only for the optimum values of the objective functions but also for robustness (that is, a small variability of these objective functions around these optima). Thus, in each problem, there is always more than one objective function, and there is a need for decision-making procedures with respect to these multiple objectives, which may involve the use of different multiple-objective optimization techniques, such as weighting, prioritizing (goal programming), objective functions as constraint equations, Pareto limiting regions or curves, etc. Thus, the treatment of uncertainties involves stochastic multi-objective optimization techniques for modeling the inverse problem.

Modeling the multiple-objective optimization problem: general aspects

The traditional optimization methods usually treat the variables of the problems as deterministic. For a review of traditional calculus-based algorithms (for the search of local optima), see references [10] and [11].

Heuristics that search for global optima have been proposed in the literature, several of which based in the imitation of behaviors found in nature. An example of this is the *survival of the fittest*, found in heuristics such as evolutionary algorithms, genetic algorithms, differential evolution, particle swarm optimization, etc (see references [12] to [14]).

But in several cases, these algorithms still consider as deterministic the problem variables (for example, the loading, boundary conditions, material properties, geometry etc) and/or parameters (for example, the coefficients in the objective functions or in the constraint equations).

Treatment of stochasticity of variables and parameters

The modeling of stochasticity both in the variables and in the parameters of a problem involves the use of probabilistic methods in engineering, such as Monte Carlo simulation, Response Surface techniques, Design of Experiments, First Order Reliability Methods (FORM) or Second Order Reliability Methods (SORM), logistic regression, etc.

The stochasticity can be also used in identification procedures in two steps: first, a set of random information is used to identify the system parameters (for example, via Kalman filter), and second, an independent set of stochastic data is used for the treatment of the random variables of the problem (see references [15], [16] on different probabilistic methods in engineering).

Decision techniques in the treatment of multiple objectives

Decision techniques regarding the multiple objectives of an optimization problem may include: weighting, assignment of priorities, the use of objective functions as constraint equations, the use of fuzzy membership functions in the decision-making process, obtaining regions or curves of Pareto limits, etc.

In certain cases, objectives of different natures may need to be considered, and their combination (through weighting, for example) may not be possible. For example, on a particular problem, one objective may happen to be written as a real function, while another objective may involve only integer numbers, and a third objective may involve only a qualitative response. In this case, a promising technique for a proper combination of these objectives of different natures could be the use of fuzzy membership functions for each objective function, looking for the optimization of one function only, namely, the summation of all the fuzzy membership functions. This technique could even allow the designer to include a bias through one or another objective function, if this is considered necessary (see references [17] and [18] on the use of fuzzy logic in optimization).

3. Main accomplishments

This research comprises the study of a direct problem (BEM model of a structure) and an inverse problem (optimization and identification techniques for damage detection), as well as the modeling of uncertainties.

The research work is being done by the Computational Mechanics group at UNIFEI (Itajubá), performed under supervision of Prof. Ariosto, and includes some collaborative work, together with professors from Vanderbilt University, University of Hawaii, Manoa and ITA ó Instituto Tecnológico de Aeronáutica, São José dos Campos, Brasil.

As results directly related to this research, several publications and monographs were published and /or are being prepared, as detailed in the Appendix. The conference papers presented and journal articles published are attached at the end of this report, for completeness.

The publications were concentrated on conference papers and journal articles, while the monographs were concentrated on thesis and dissertations defended by the graduate students involved in this work, and also a technical report for the analysis of vibration data related to dynamic components of a helicopter, on the context of HUMS ó Health and Usage Monitoring Systems.

Besides the published work and the defended thesis and dissertations, some research papers and student thesis/dissertation defenses are also expected to occur in the near future, related to this work. The list in the Appendix includes the on-going research, leading to student dissertations / thesis.

The research goals for this work include the increase in the complexity of the modeling of the direct and inverse problems, in order to:

- for the direct model: to reproduce as close as possible the reality of an aircraft structure, and
- for the inverse model: to give reliable damage information, through a combination of independent optimization and identification procedures to indicate location and size for the structural damage.
- for both models: to account for the uncertainties in the model.

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3.1 Establishment of collaborative research work (on-going work)

The research on the modeling and simulation of the inverse problem has involved some collaborative work with Prof. G. Walker from Vanderbilt University (Nashville, TN) (potential problems), and with Prof. Marcelo Kobayashi, from University of Hawaii, Manoa (topological optimization). This collaboration was very important for discussing modeling techniques for the inverse problem. Furthermore, this collaboration has created a synergy between the computational mechanics group from UNIFEI in Brazil and both Vanderbilt University and University of Hawaii, Manoa, important for the planned modeling of the uncertainties of the damage detection problem. In particular, the collaboration with Prof. G. Walker has led to a co-advising of a graduate student at Vanderbilt, on inverse methods to potential problems, and as a spin-off from the collaboration with Prof. Marcelo Kobayashi, a student is currently being advised at UNIFEI on the use of topological optimization in inverse methods.

To start-up this collaborative work, Prof. Ariosto has done technical visits to both Vanderbilt University and University of Hawaii, Manoa, as a short-term visiting scholar, while continuing to coordinate the research work being done by the students and researchers from the UNIFEI research group, in Brazil.

Also, a collaborative work was done with three professors from ITA - Instituto Tecnológico de Aeronáutica, São José dos Campos, Brazil. The collaborative work with Prof. Donizeti de Andrade, on detection of failures of a helicopter main rotor, has led to a co-advising of a graduate student at ITA. The collaborative work with Professors Bento de Mattos and Airton Nabarrete has led to a technical report on the analysis of vibration data related to dynamic components of a helicopter, on the context of HUMS ó Health and Usage Monitoring Systems.

References

- [1] Raghavan, A & Cesnik, CES (2005): Lamb Wave-based Structural Health Monitoring, Book Chapter in *Damage Prognosis* Editors: Inman, DJ; Farrar, CR; Lopes Jr., V; & Steffen Jr., V. Wiley.
- [2] Cesnik, CES & Raghavan, A (2008): Fundamentals of Guided Elastic Waves in Solids, Chapter in *Encyclopedia of Structural Health Monitoring* Editors: Cheng, F-K & Boller C, Wiley, to appear.
- [3] Giurgiutiu, V; Joshi, S, et al. (2007): Structural health monitoring with piezoelectric wafer active sensors for space applications, AIAA JOURNAL, V. 45, p. 2838-2850.
- [4] Banks, HT; Inman, DJ; Leo, DJ & Wang, Y (1996): An experimentally validated damage detection theory in smart structures, *Journal of Sound and Vibration*, 191, 5 (1996), 859-880.
- [5] Burczynski, T & Beluch, W (2001): The identification of cracks using boundary elements and evolutionary algorithms, *Engineering Analysis with Boundary Elements*, 25 (2001), pp. 313-322.
- [6] Aliabadi, MH & Rooke, DP (1991): *Numerical fracture mechanics*, Computational Mechanics Publications. Dordrecht: Kluwer Academic Publishers.
- [7] Tada, H; Paris, PC & Irwin, GR (2000): *The stress analysis of cracks handbook*, 3rd edn, ASME: ASME, New York.

AFOSR/SOARD Grant FA9550-10-1-0103. Report 2010-13. PI: Dr. Ariosto B Jorge. Numerical Modeling of Inverse Problems under Uncertainty for Damage Detection in Aircraft Structures.

- [8] Soares, D; Mansur, WJ; Von Estorff, O (2007): An efficient time-domain FEM/BEM coupling approach based on FEM implicit Green's functions and truncation of BEM time convolution process, *Computer Methods in Applied Mechanics and Engineering*, V. 196, 9-12, p. 1816-1826.
- [9] Soares, D; Mansur, WJ (2007): An efficient stabilized boundary element formulation for 2D time-domain acoustics and elastodynamics, *Computational Mechanics*, V. 40, 2, p. 355-365.
- [10] Nash, SG; Sofer, A (1996): *Linear and nonlinear programming*, McGraw-Hill.
- [11] Vanderplaats, GN (1984): *Numerical optimization techniques for engineering design*, McGraw-Hill.
- [12] Bäck, T; Schwefel, H-P (1993): An overview of evolutionary algorithms for parameter optimization, *Evolutionary Computation* 1, 1 (1993), 1-23.
- [13] Michalewicz, Z (1995): *Genetic Algorithms + Data Structures = Evolutionary Programs*, 3rd ed. Springer.
- [14] Toffolo, A; Lazzaretto, A (2002): Evolutionary algorithms for multi-objective energetic and economic optimization in thermal system design. *Energy*. V.27, no.6, pp. 549-567.
- [15] Haldar, A; Mahadevan, S (1999): *Probability, Reliability, and Statistical Methods in Engineering Design*, Wiley.
- [16] Montgomery, DC; Runger, GC (2007): *Applied Statistics and Probability for Engineers*, 4th Edition, Wiley.
- [17] Rao, SS; Xiong, Y (2005): Mixed-Discrete Fuzzy Multiobjective Optimization of Structures using a Hybrid Genetic Algorithm, *6th World Congress on Structural and Multidisciplinary Optimization*, Rio de Janeiro, 30 May - 03 June 2005, Brazil.
- [18] Xiong, Y; Rao, SS (2004): Fuzzy nonlinear programming for mixed-discrete design optimization through hybrid genetic algorithm, *Fuzzy Sets and Systems*, 146, pp. 167-186.

Appendix

A1. Related Publications: Conference papers (presented)

1. Myers, MR; Jorge, AB; Mutton, MJ; Yuhas, DE; Walker, DG (2012): A Novel Ultrasonic Method for Locating the Boundary Layer Transition Region on a Hypersonic Vehicle. *Proceedings of 50th AIAA Aerospace Sciences Meeting - AIAA-2012-0859*, January 9-12, 2012, Nashville, TN, USA.
2. Myers, MR; Jorge, AB; Walker, DG; Mutton, MJ (2011): Heat Source Localization Sensitivity Analyses for an Ultrasonic Sensor Array, *Proceedings of ASME/JSME 8th Thermal Engineering Joint Conference - AJTEC 2011*, March 14-17, 2011, Honolulu, Hawaii, USA.
3. Vieira, BADB; Jorge, AB; Lopes, PS; Cunha Junior, SS (2011): A Kalman Filter Model for an Inverse Problem of Localization and Identification of Damage Parameters on a 2-D Structure. *Proceedings of XXXII Iberian Latin-American Congress on Computational Methods in Engineering - CILAMCE*, 2011, Ouro Preto.

AFOSR/SOARD Grant FA9550-10-1-0103. Report 2010-13. PI: Dr. Ariosto B Jorge. Numerical Modeling of Inverse Problems under Uncertainty for Damage Detection in Aircraft Structures.

4. Myers, MR; Jorge, AB; Walker, DG; Mutton, MJ (2010): A Comparison of Extended Kalman Filter, Extended Information Filter, and Least Squares Approaches for Parameter Identification of a Transient Heat Transfer Problem. *Proceedings of Inverse Problems Symposium - IPS*, June 6 - 8, 2010, Michigan State University, USA.
5. Myers, MR; Jorge, AB; Walker, DG (2010): A Comparison of Extended Kalman Filter Approaches Using Non-Linear Temperature and Ultrasound Time-Of-Flight Measurement Models for Heating Source Localization of a Transient Heat Transfer Problem. *Proceedings of Inverse Problems, Design and Optimization Symposium - IPDO*, Aug 25-27, 2010, João Pessoa, Brazil.
6. Ribeiro, TSA; Ribeiro, GO; Jorge, AB (2010): A Numerical Convergence Study of the Relaxed Continuity Approach for Self-Regular Traction-BIE. *Proceedings of 11th Pan-American Congress of Applied Mechanics - PACAM XI*, Jan 04-08, 2010, Foz do Iguaçu, PR, Brazil.

A2. Related Publications: Journal articles (published)

1. Myers, MR; Jorge, AB; Yuhas, DE; Walker, DG (2013): Using Ultrasound and the Extended Kalman Filter for Characterizing Aerothermodynamic Environments, *AIAA Journal*, accessed August 01, 2013, doi: 10.2514/1.J052313 (<http://arc.aiaa.org/doi/abs/10.2514/1.J051609>)
2. Myers, MR; Jorge, AB; Mutton, MJ; Walker, DG (2012): A comparison of extended Kalman filter, ultrasound time-of-flight measurement models for heating source localization, *Inverse Problems in Science & Engineering*, v.20, Issue 7, p. 991-1016.
3. Myers, MR; Jorge, AB; Mutton, MJ; Walker, DG (2012): A comparison of extended Kalman filter, particle filter, and least squares localization methods for a high heat flux concentrated source, *International Journal of Heat and Mass Transfer*, v. 55, p. 2219-2228.
4. Myers, MR; Jorge, AB; Mutton, MJ; Walker, DG (2012): High heat flux point source sensitivity and localization analysis for an ultrasonic sensor array, *International Journal of Heat and Mass Transfer*, v. 55, p. 2472-2485.
5. Myers, MR; Jorge, AB; Yuhas, DE; Walker, DG (2012): An Adaptive Extended Kalman Filter Incorporating State Model Uncertainty for Localizing a High Heat Flux Spot Source Using an Ultrasonic Sensor Array, *Computer Modeling in Engineering & Sciences*, v. 83, p. 221-248.
6. Lopes, OS; Jorge, AB; Cunha Jr, SS (2010): Detection of holes in a plate using global optimization and parameter identification techniques, *Inverse Problems in Science & Engineering*, v. 18, p. 439-463, 2010.

A3. Related Student Dissertations / Thesis (defended)

1. **Title:** Parameter Estimation Using Extended Kalman Filter and Ultrasonic Pulse Time of Flight to Locate Transient, Concentrated Heating Sources. **Type of monograph:** PhD Dissertation in Mechanical Engineering (Vanderbilt University). **Author:** Michael Richard Myers. **Advisor:** Prof. D. Greg Walker. **Co-advisor:** Prof. Ariosto Bretanha Jorge. **Defense date:** March 2012.
2. **Title:** Application of the Kalman filter for a 2-D Inverse Problem of Damage Detection and Localization (in Portuguese) (Aplicação de Filtro de Kalman para um Problema Inverso de

AFOSR/SOARD Grant FA9550-10-1-0103. Report 2010-13. PI: Dr. Ariosto B Jorge. Numerical Modeling of Inverse Problems under Uncertainty for Damage Detection in Aircraft Structures.

Localização e Detecção de Dano em Problema 2-D). **Type of monograph:** Master's Thesis in Mechanical Engineering (UNIFEI). **Author:** Bruno André Duarte Braz Vieira. **Advisor:** Prof. Ariosto Bretanha Jorge. **Defense date:** 2011.

3. **Title:** Predictive Analysis in Failure Detection on the Main Rotor, Focused in Helicopter Vibration using HUMS Approach (in Portuguese) (Análise Preditiva na Detecção de Falhas no Rotor Principal com Foco na Vibração em um Helicóptero Segundo a Filosofia HUMS). **Type of monograph:** Master's Thesis in Aeronautical and Mechanical Engineering (Instituto Tecnológico de Aeronáutica - ITA). **Author:** Rafael de Abreu González. **Advisor:** Prof. Domizeti de Andrade. **Co-advisor:** Prof. Ariosto Bretanha Jorge. **Defense date:** 2011.
4. **Title:** Modeling of Inverse Problem of Damage Detection using Parameter Identification and Global Optimization Techniques (in Portuguese) (Modelagem de Problema Inverso de Detecção de Danos por Técnicas de Identificação de Parâmetros e de Otimização Global). **Type of monograph:** PhD Dissertation in Mechanical Engineering (UNIFEI). **Author:** Patricia da Silva Lopes. **Advisor:** Prof. Ariosto Bretanha Jorge. **Co-advisor:** Prof. Sebastião Simões da Cunha Jr. **Defense date:** December 2010.

A4. Related Student Dissertations / Thesis (on-going research)

1. **Title:** Multi-Objective Stochastic Optimization in Aeronautical Structure under Aerodynamic Loadings, with Aeroelastic Coupling (in Portuguese) (Otimização Estocástica Multi-Objetivos em Estrutura Aeronáutica sujeita a Carregamentos Aerodinâmicos, com Acoplamento Aeroelástico). **Type of research:** Doctoral Studies in Mechanical Engineering (UNIFEI). **Student:** Bruno Silva de Sousa. **Advisor:** Prof. Ariosto Bretanha Jorge. **Co-advisor:** Prof. Sebastião Simões da Cunha Jr.
2. **Title:** Application of Topologic Optimization Techniques in the Sensor Configuration for Maximization of the Probability of Localization and Identification of Damages (in Portuguese) (Aplicação de Técnicas de Otimização Topológica na Configuração de Sensores para Maximização da Probabilidade de Localização e Identificação de Danos). **Type of research:** Doctoral Studies in Mechanical Engineering (UNIFEI). **Student:** Adriana Amaro Diacenco. **Advisor:** Prof. Ariosto Bretanha Jorge. **Co-advisor:** Prof. Sebastião Simões da Cunha Jr.
3. **Title:** Inverse Problem of Modal Identification of an Aeronautical Structure using Kalman Filter (in Portuguese) (Problema Inverso de Identificação Modal de uma Estrutura Aeronáutica Através de Filtro de Kalman). **Type of research:** Masters Studies in Mechanical Engineering (UNIFEI). **Student:** Milena Ponce de León Antunes Popovic. **Advisor:** Prof. Ariosto Bretanha Jorge. **Co-advisor:** Prof. Rogério Frauendorf de Faria Coimbra.

A5. Technical Reports

1. Jorge, AB; Chiarello, AG; Nabarrete, A; Mattos, B; Angelo, M; Mont'Alverne, A (2012): System Errors (Signal/Electrical Errors): Case Study and Proposed Error Indicators, *HUMS Group UNIFEI/ITA/ HELIBRAS Technical Report*, December 14.

Note: the conference papers presented, the journal articles published, and the technical report are attached at the end of this report, for completeness.